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Carboxyhemoglobin Levels During A Submarine Patrol

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One of the major contaminants from tobacco smoking aboard a nuclear submarine is carbon monoxide (CO). While this gas is controlled to 15 parts per million or lower by catalytic burners, there still remains a residual low level in the atmosphere. This study has shown that, on one submarine, the average ambient concentration was 7 ppm, which produced an average carboxyhemoglobin level in 15 nonsmokers of 2.1%, 1.7%, and 1.7% at the start, middle, and end of a 40-d patrol. Because submariners are generally healthy and young, it is concluded that CO exposures at these ambient levels do not constitute a major risk factor to the physiological well-being of these submariners, nor are they expected to cause any decrement in performance.

ONE OF THE MAJOR contaminants from tobacco smoking in the closed recirculated atmosphere of a nuclear submarine is carbon monoxide (CO). While catalytic burners maintain ambient CO below the required level of 15 parts per million (ppm), a submarine maintained at an average concentration of about 9 ppm will induce a carboxyhemoglobin (COHb) level of 2% in a nonsmoking crew member. The CO limit for an 8-h period in an occupational environment is set at 50 ppm (6), and the 8-h limit for ambient air has been set at 8.7 ppm. This latter value protects against the occurrence of a 2% COHb in the nonsmoking public (7). It would seem, therefore, that although the submarine maintains an occupationally safe level of CO, its crew members may, in fact, be subjected to a higher CO level than that recommended for the general public.

The purpose of this study was to measure the COHb level in the crew members of a nuclear submarine during a lengthy underwater patrol, and to determine from an evaluation of the current literature if the levels obtained could be detrimental to the health or impair the performance of these submariners.

MATERIALS AND METHODS

Of the 65 men who volunteered for the experiment, 20 smokers and 20 nonsmokers were randomly chosen to participate. Blood samples were drawn 2 weeks before the start of the patrol, and on the 3rd, 22nd, and 36th days of the scheduled 40-d patrol. All blood samples were drawn within 30 min after the subject had awakened, except for the pre-patrol samples when some subjects were awake for up to 90 min. Additionally, on the

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22nd day of the patrol, another blood sample was drawn just before the subjects retired.

Venous blood was drawn from an anticubital vein into a heparinized Vacutainer®, and all samples were analyzed within 1 h for carboxyhemoglobin and hemoglobin on an Instrumentation Laboratory Co-Oximeter 182. It was recognized that the resolution and accuracy of this apparatus is not ideal for low values of COHb (12), but it was used because of its compatability with measurements aboard a submarine. Simultaneously with 87 of these blood draws, the carbon monoxide in the breath was measured with an Ecolyzer CO analyzer according to the methods outlined by Jones *et al.* (10). Statistical analysis was done using the Student's paired t-test.

RESULTS

COHb levels of nonsmokers during the submerged period did not differ significantly from those obtained while the submarine was surfaced before the patrol (Table I). The values, as expected, reflected ambient CO levels. On the third day of the patrol, 9 of 15 nonsmokers exceeded a COHb concentration of 2%. Smokers' COHb levels while submerged likewise did not differ from pre-submerged values when considerations were made for the number of cigarettes smoked prior to blood-draw during the pre-patrol measurement period. After 6-10 h of sleep, smokers' COHb levels remained at more than twice those of nonsmokers (Table II). It may also be seen that nonsmokers' COHb levels did not rise significantly during their waking hours, but the COHb of smokers doubled in value.

A strong relation was found (r = 0.93) between alveolar breath CO (ppm) and simultaneously-determined blood carboxyhemoglobin in 87 samples from the 20 smokers and 20 nonsmokers. The regression equation for this relationship was COHb = 0.157 CO (breath) + 0.931.

TABLE I. MEAN AND STANDARD DEVIATION OF %COHb LEVELS OF SUBMARINERS UPON AWAKENING.

		Pre-Patrol	Patrol		
			+3 Days	+22 Days	+36 Days
NONSMOKERS (n=15)		1.67(.214)*	2.08(.229)	1.72(.420)	1.72(.346)
SMOKERS (n=15)	(A)	† 3.50(1.47)			
	(B)	4.60(1.43)	3.83(.786)	3.69(1.18)	3.67(1.72)
	(C)	5.10(1.42)			
AMBIENT CO IN ppm MEAN (Max)		3 (3)	7 (10)	7 (7)	5 (6)

*COHb changes during the patrol were not significantly different from those obtained pre-patrol.

†Some smokers did not refrain from smoking after awakening and before blood samples were drawn during the pre-patrol period. Accordingly, Group A (n=4) did not smoke, Group B (n=6) smoked 1 or 2 cigarettes, and Group C (n=7) smoked an average of 6 cigarettes.

TABLE II. MEAN AND STANDARD DEVIATION OF %COHb LEVELS OF SUBMARINERS UPON AWAKENING AND UPON RETIRING ON THE 22nd DAY OF THE PATROL.

	SMOKERS		NONSMOKERS	
	Upon Awakening	Upon Retiring	Upon Awakening	Upon Retiring
	3.79 (1.20)	6.45 (2.18)	1.71 (.40)	1.78 (.36)
n	13		12	
p	<.001		>.2	

TABLE III. PERCENT HEMOGLOBIN LEVELS OF SUBMARINERS UPON AWAKENING.

	PRE-PATROL	PATROL		
	A	B +3 Days	C +22 Days	D +36 Days
NONSMOKERS Mean (S.D.) n = 15	16.9 (.92)	16.4 (1.0)	16.9 (.81)	16.3 (.98)
SMOKERS Mean (S.D.) n = 16	16.6 (.89)	16.3 (.91)	16.6 (.83)	16.1 (.82)

Significant differences ($p \leq .05$) between periods for the various groups are as follows: For non-smokers, A compared with B, A with D, B with C, and C with D; for smokers, A compared with D, B with D, and C with D.

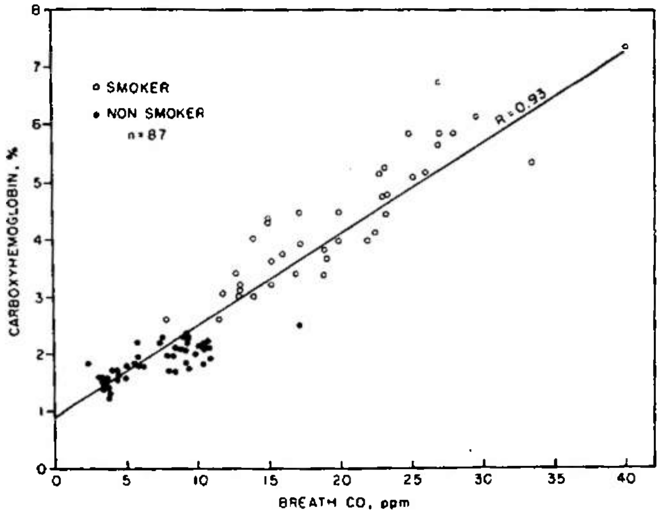

Fig. 1. Blood CO levels are shown to vary linearly (slope = 0.157; intercept = 0.931) with the measured breath CO levels.

Hemoglobin values, determined from venous blood samples drawn for COHb measurements, are presented in Table III. During the beginning (+3 days) and end (+36 days) of the patrol, hemoglobin values were significantly lower than the pre-patrol or middle (+22 days) patrol levels.

DISCUSSION

The primary sources of carbon monoxide in the closed recirculated atmosphere of a nuclear submarine are tobacco smoke, engine exhaust, and cooking. This generated carbon monoxide is catalytically burned and is not allowed to exceed 15 ppm. The submarine studied in this report had an average ambient CO level of 7 ppm for the 40-d mission, which produced in its nonsmoking crew an average COHb level of 1.7%, confirming the works of Goldsmith and Landaw (8), McIlvaine *et al.* (13), and Coburn *et al.* (4), which predicted that an ambient CO concentration of 7 ppm would produce in the nonsmoker a COHb concentration of 1.5 - 1.8%. The control value of 1.67% obtained in this study is considerably higher than that which would have been predicted from the control ambient level of 3 ppm. This may have been due in part to two or three subjects who reported themselves as nonsmokers at the start of the study but had, in fact, given up cigarette smoking either just before their bloods were drawn or on the evening preceding the blood draw.

Smoking subjects had twice the COHb concentrations as nonsmokers when the samples were obtained upon awakening, and over 3.5 times greater when samples were taken before retiring. We could not determine from these data what effect ambient CO had on the COHb levels of our smoking subjects. Studies carried out on British submariners indicate that smoking and ambient CO levels affect carboxyhemoglobin in an additive way (D. M. Davies, personal communication). The values obtained for smokers, however, are not dissimilar to those observed for the smoking public (13,17).

Long-term exposure of animals to low levels of CO results in an adaptive response of the erythropoetic system and also elicits an increase in hemoglobin concentration (14). This has been shown to occur before on submarines where the CO concentration was 15-20 ppm (19). The results of the present study show no consistent rise in hemoglobin but show an oscillating effect instead. The slightly elevated carbon dioxide of 0.5-0.8% in the submarine atmosphere would tend to increase breathing rate and would, to some extent, counteract the hypoxic stimulus of a slightly increased COHb level. Therefore, when ambient CO is below 10 ppm and the carbon dioxide level is near 0.5%, the stimulus to produce more red blood cells may be near the physiological response threshold.

The COHb levels of 3% or less determined in this study, and those which may be expected to occur in the nonsmoking crews of other submarines, are well below the level at which significant decrements in performance and physiological impairment are known to occur. It appears that, at COHb concentrations less than 10%, a crew member's ability to perform complex tasks requiring both judgment and motor coordination should not be adversely affected (18; D. M. Davies, personal communication). Likewise, studies of vigilance performance (3) and visual processes (11) indicate that COHb levels much higher than those expected to occur aboard submarines are needed before deficiencies are expected.

The submarine crew is young and generally free from any debilitating disease. Thus, while it has been demonstrated that specifically impaired individuals, such as those with coronary heart disease or other diseases which severely limit oxygen delivery, will be further compromised by exposure to low levels of CO (1,2), it is highly unlikely that the bodily functions of a healthy submariner will be adversely affected by COHb levels less than 4%. At levels greater than 4%, decreases in maximum oxygen consumption and work endurance have been observed among healthy subjects (9,15).

Little research has been directed toward the possible adverse effects of chronic long-term exposure of humans to seemingly innocuous low levels of CO. In a medical study of 156 Holland Tunnel workers exposed to average CO concentrations of 70 ppm throughout the course of a work day for a period lasting 13 years, the medical examiners concluded that these men suffered no occupationally related diseases and, in fact, were found to be in excellent physical condition (16). Based on an 8-h work day, 5 days per week, and a 50 week year, the yearly occupational CO exposures for these men was 134,000 ppm hours. Submariners, exposed to an average concentration of 7 ppm, 24 h/d, 7 days a week for two 3-month periods during the year, are subjected to a yearly occupational CO exposure of 28,244 ppm hours, nearly one-fifth the exposure for tunnel workers. It is interesting to note that the average CO concentration in eight major U. S. cities during the years 1962-1967 was 7.7 ppm (5). This would expose the urban dweller to 67,452 ppm hours during a year.

While the data reported in this paper is limited to one submarine, it serves to emphasize two important facts.

The first is that ambient CO concentrations, maintained at a relatively low level by the use of highly efficient catalytic burners, are considerably below those found in other occupational exposures and not unlike those found in urban air. Second, the COHb values of nonsmoking crew members are near what would have been predicted from the measured ambient CO levels and, more importantly, these COHb concentrations are not likely to have affected the behavioral or the physiological well-being of the crew to any measurable extent.

The effects of chronic low-level exposure to CO in combination with a chronic low-level exposure to other submarine contaminants, such as carbon dioxide, nitrogen dioxide, and ozone, on the cardiovascular, respiratory, and neurohumoral systems have yet to be determined.

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